Search for supersymmetry at CMS in final states with a single lepton, jets, and missing momentum

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CMS PAS SUS-11-015

Signature, Backgrounds, and Predictions

- Search for SUSY in 1 isolated lepton + jets + MET channel
  - 1 isolated lepton from decay of a W or new particle
  - high-energetic jets from the decays of strongly-coupled SUSY particles
  - MET from the weakly-interacting LSPs
- Backgrounds
  - W+jets & ttbar: largest backgrounds, requirement of p_T jets and high $H_T = \sum_{jets} p_T^j$ reduces this background
  - QCD: suppressed by multiple energetic jets, isolated lepton, and large MET
- Two approaches for final selection and background estimation
  - Lepton Spectrum method
    - Uses lepton p_T spectrum to predict major background, 1-lepton SM ttbar & W+jets
  - Lepton-Projection (L_P) Method
    - Sensitive to helicity angle of lepton in W rest frame (developed in context of W polarization measurement)

Data-driven methods and reliance on W polarization

- Both lepton spectrum and lepton projection methods data-driven and rely on well understood properties of W polarization
- For ttbar, W polarization very precise prediction of SM theory, calculated to NNLO [f_0=0.687±0.005, f_+=0.0017±0.0001, f_-=0.311±0.005]. D0 and CDF measurements agree with the theory prediction.

Theory: doi/10.1103/PhysRevD.81.111503
D0: doi/10.1103/PhysRevLett.107.021802
CDF: doi/10.1103/PhysRevLett.105.042002

- For W+jets, theory calculates W polarization to NLO and helicity fractions stable with respect to QCD corrections. Experimental measurement at CMS (based on the L_P variable used in this SUSY search) consistent with theory.

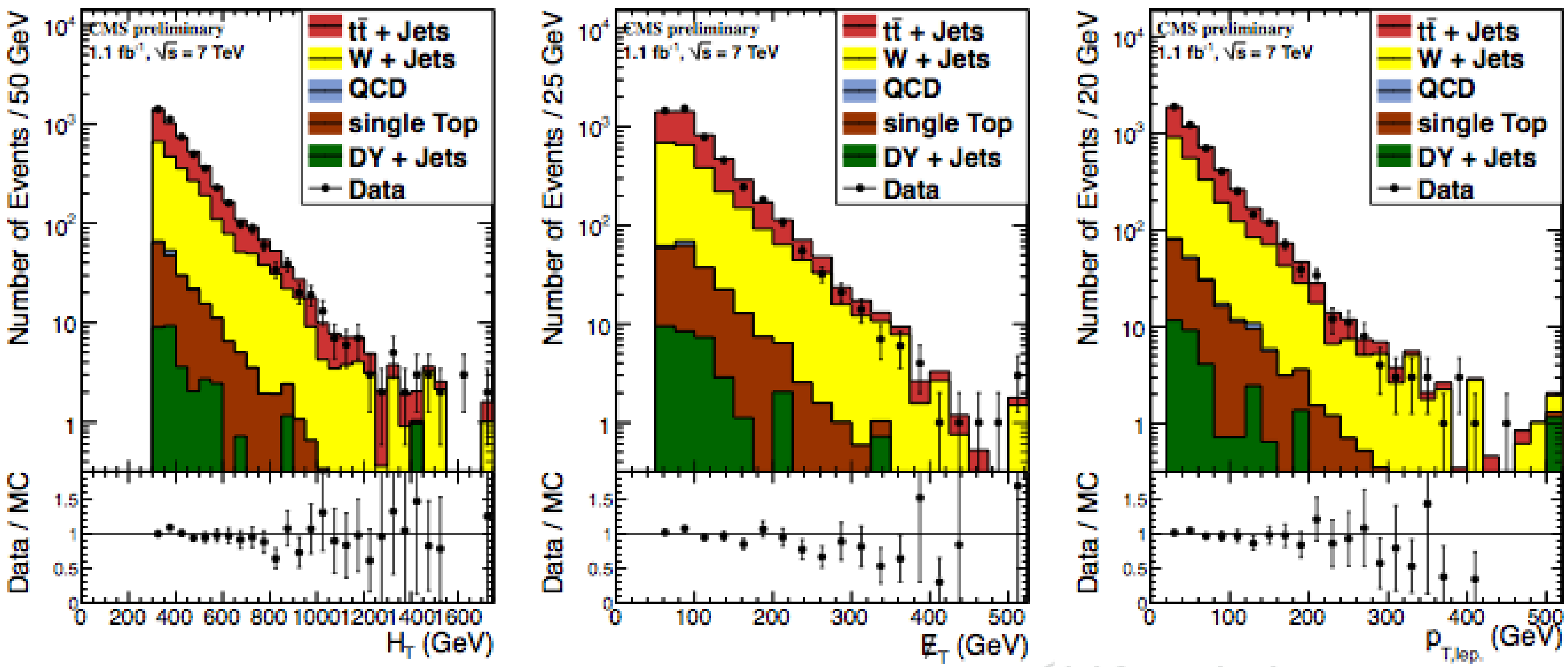
Theory: arXiv:1103.5445
CMS: doi/10.1103/PhysRevLett.107.021802

Event Preselection Requirements

Quantity	Requirement
Jet p_T threshold	> 40 GeV
Jet η range	$\lvert\eta\rvert < 2.4$
Number of jets	≥ 3 (LP Variable method), ≥ 4 (Lepton Spectrum method)
Lepton p_T threshold	> 20 GeV
Muon η range	$\lvert\eta\rvert < 2.1$
Muon isolation (relative)	< 0.10
Electron isolation (relative)	< 0.07 (barrel), < 0.06 (endcaps)
Electron η range	$\lvert\eta\rvert < 2.4$, excluding barrel-endcap overlap
Lepton p_T threshold for veto	> 15 GeV

All results in this talk for 1.1 fb^{-1}

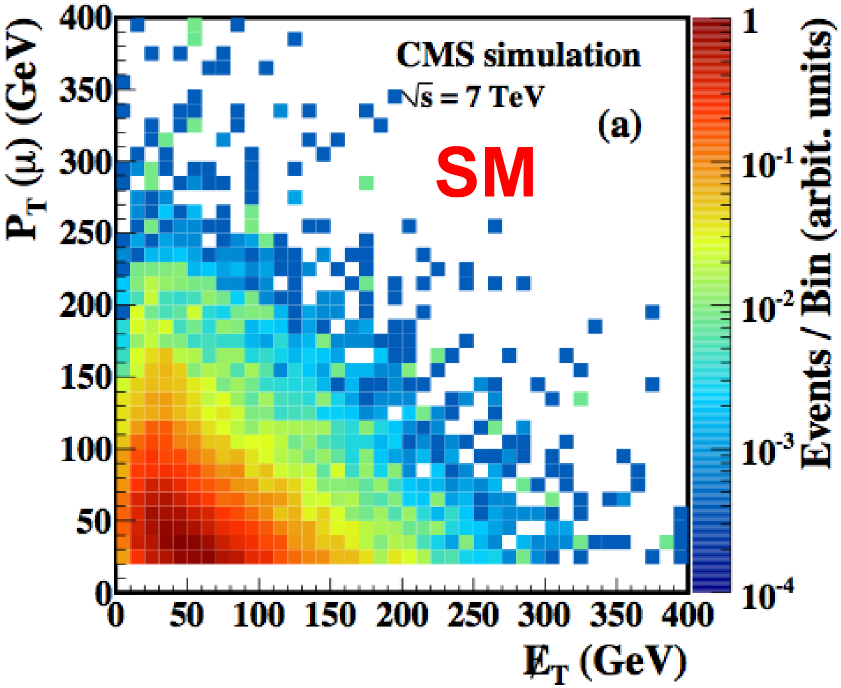
Plots made for $\geq$3 jets, exactly 1 muon w/ p_T>20 GeV, H_T>300 GeV, MET>60 GeV

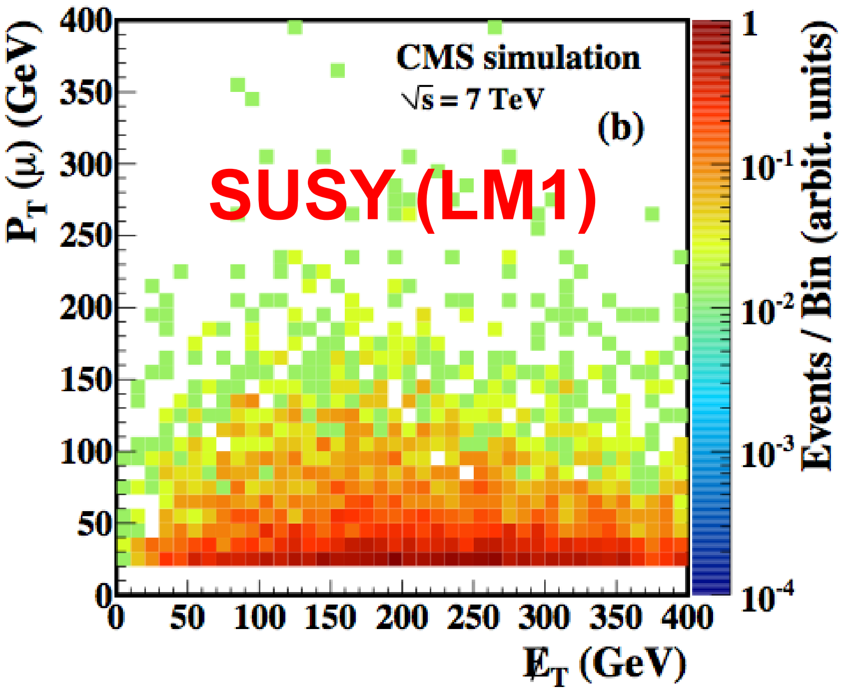


MC scaled to data; good agreement between data and MC shapes

Lepton Spectrum Method

Lepton p_T and MET distributions





- In SM (ttbar and W+jets), the MET (neutrino p_T) and lepton p_T spectra are closely related. Differences stem from:
  - W-polarization in ttbar and W+jets, lepton selection criteria, feed-down from dilepton and τ events
  - MET instrumental resolution and systematic mismeasurements (modeled using QCD data)
- In SUSY, the MET and lepton p_T spectra decouple due to the presence of two LSPs. MET spectra tend to be much harder than the lepton p_T spectra in many models

Lepton Spectrum Method

Search in MET tail with ≥**4 jets and H_T>500**. In ttbar & W+jets, genuine MET from neutrinos dominant source of MET, instrumental MET less important. Method models both types of MET using data-driven methods.

Background prediction methods

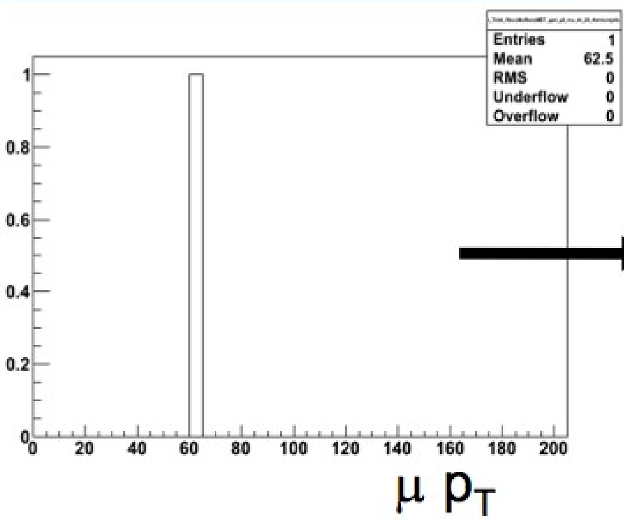
1. Single lepton ttbar and W+jets background (~75%) is modeled based on lepton p_T spectra (for real MET) smeared with artificial MET templates (for fake MET).
2. For dilepton ttbar and $\tau \rightarrow \mu$/e decays (~25%) backgrounds estimated using different methods with dilepton and single lepton control samples in the data.
3. QCD background (<1%) is constrained in data-driven way by calculating ratio of non-isolated to isolated leptons at low MET and then multiplying this ratio by non-isolated leptons at high MET.
4. Other backgrounds (<1%) are small and obtained from MC.

Method used in 2010 SUSY single lepton analysis at CMS: arXiv:1107.1870

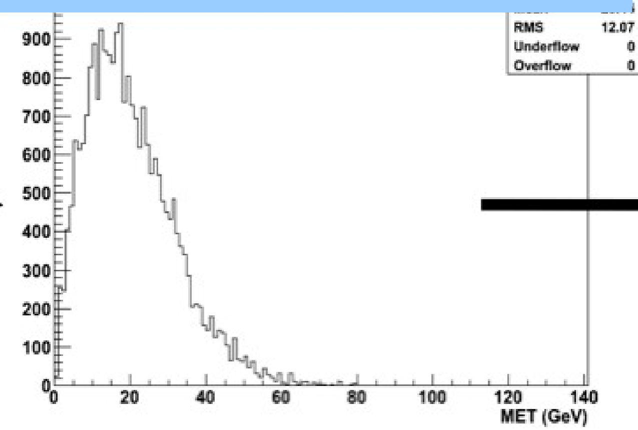
MET resolution: smearing of lepton p_T spectrum

- To model instrumental MET resolution effects, lepton p_T spectra are smeared using artificial MET templates obtained in data (from single jet triggers). The smearing procedure for 1 mu+jets events:

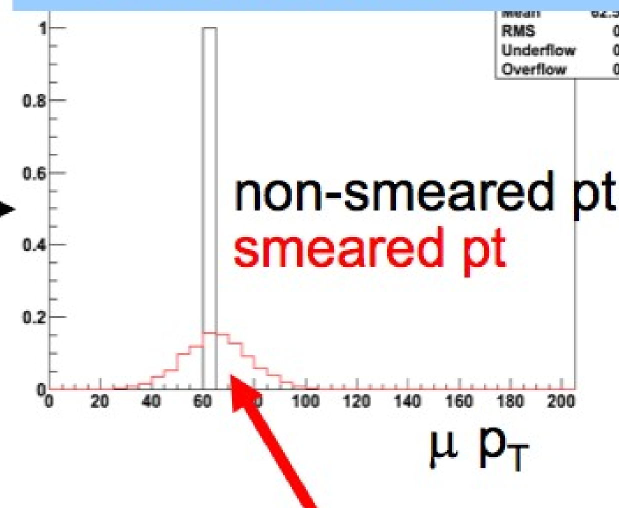
1) Start with single event



2) Find MET template corresponding to events H_T

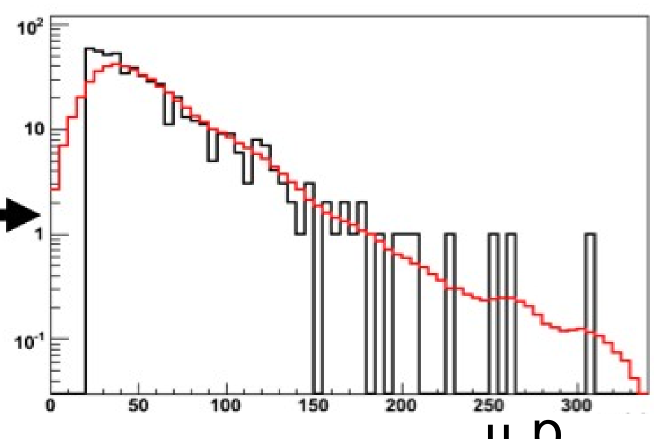


3) Smear μ p_T according to MET template.



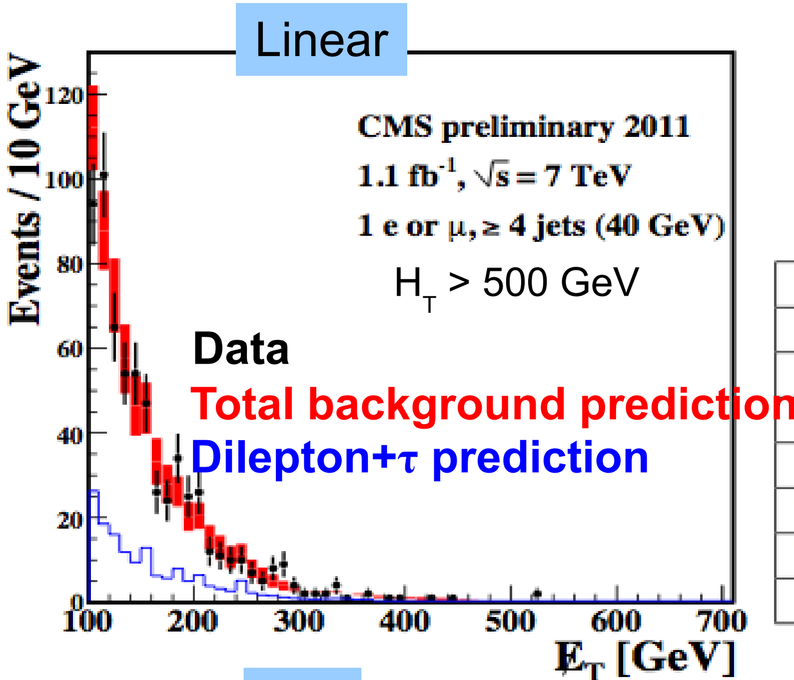
Turn 1 event into ~1000 smeared events w/ weight 0.001

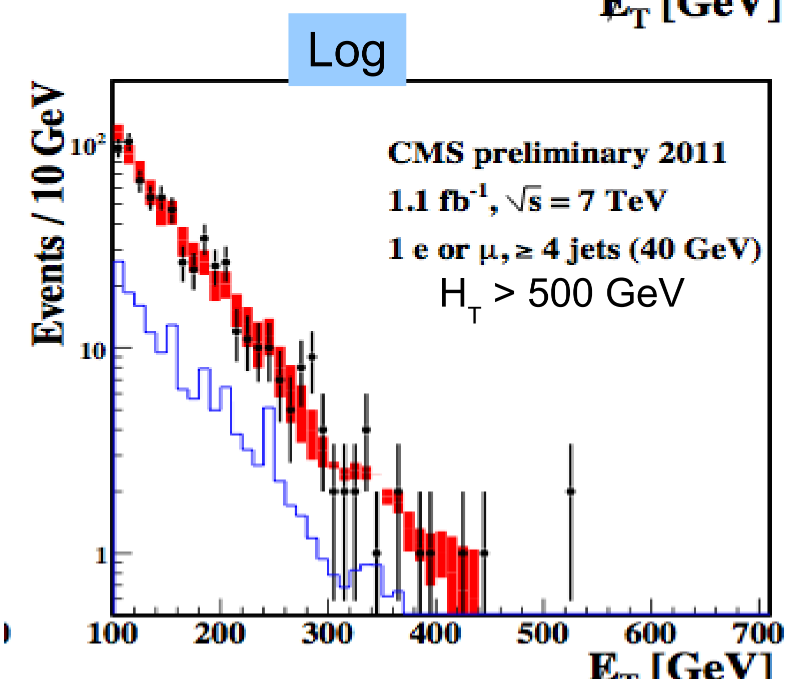
Final Result: Smeared μ pt distribution, 10-15% effect



Full MET prediction is sum of smeared lepton p_T over all single lepton events

Results for Lepton Spectrum Method





<u>Two signal selections</u>

Loose: H_T>500, MET>250 GeV

Tight: H_T>500, MET>350 GeV

Sample	Loose Selection (e+μ)	Tight Selection (e+μ)
Predicted SM 1 ℓ	$34.6 \pm 7.7 \pm 10.8$	$8.8 \pm 3.7 \pm 3.4$
Predicted SM dilepton	$4.0 \pm 3.9 \pm 0.8$	$0.9 \pm 1.9 \pm 0.9$
Predicted single τ	$10.5 \pm 1.2 \pm 0.5$	$2.3 \pm 0.5 \pm 0.2$
Predicted QCD background	$0.0 \pm 1.2 \pm 0.3$	$0.0 \pm 1.0 \pm 0.3$
Single top (MC), Z+jets (MC)	$0.7 \pm 0.2 \pm 0.2$	$0.1 \pm 0.1 \pm 0.1$
Total predicted SM	$49.8 \pm 8.8 \pm 10.8$	$12.1 \pm 4.3 \pm 3.6$
Data	52	8

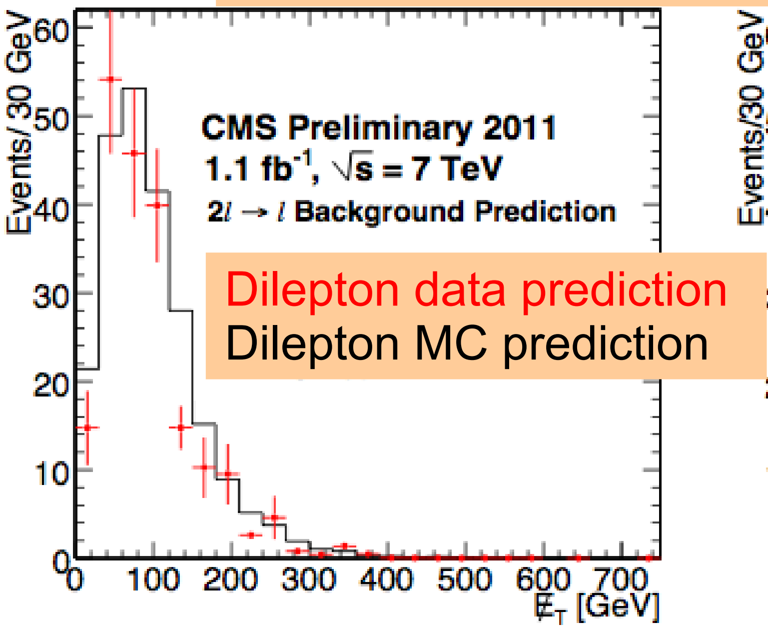
- SM 1 lep from smeared muon p_T spectra
- Predicted SM dilepton and single τ method described on next slide
- QCD background constrained to be negligible using data-driven technique
- Single top, Z+jets are very small and taken from MC
- Dominant systematic uncertainty is JES (see backup slides)

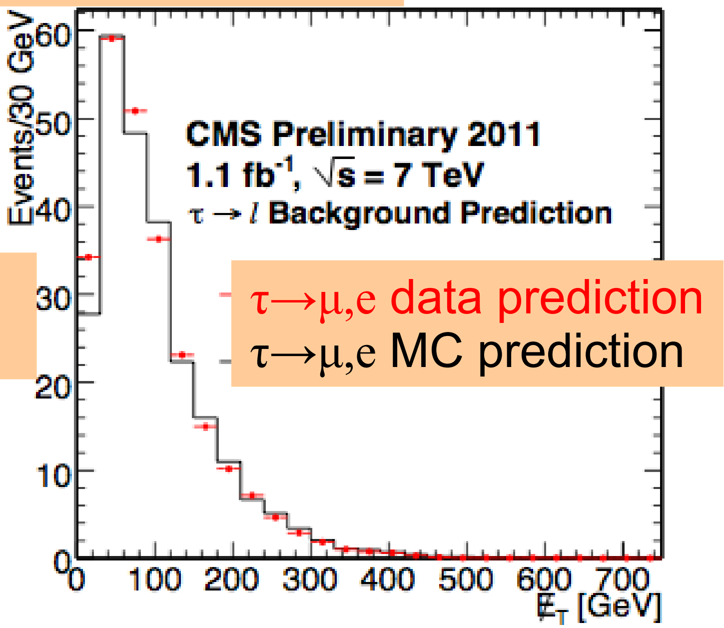
Total predicted SM agrees well with observed in both loose and tight selection

Dilepton & $\tau\rightarrow\mu/e$ backgrounds

- Lepton p_T spectrum does not predict MET from these backgrounds
  - Dilepton ttbar events: ~15% of total (from MC).
    - Use control sample of dilepton events (i.e. [μ,μ], [e,e], [μ,e]) to estimate the MET tail of these events
  - ttbar, W+jets $\tau\rightarrow\mu/e$ events: ~10% of total (from MC).
    - Use control sample of 1e/μ to predict MET by taking part of the lepton p_T and vectorially adding it to the MET (based on MC)

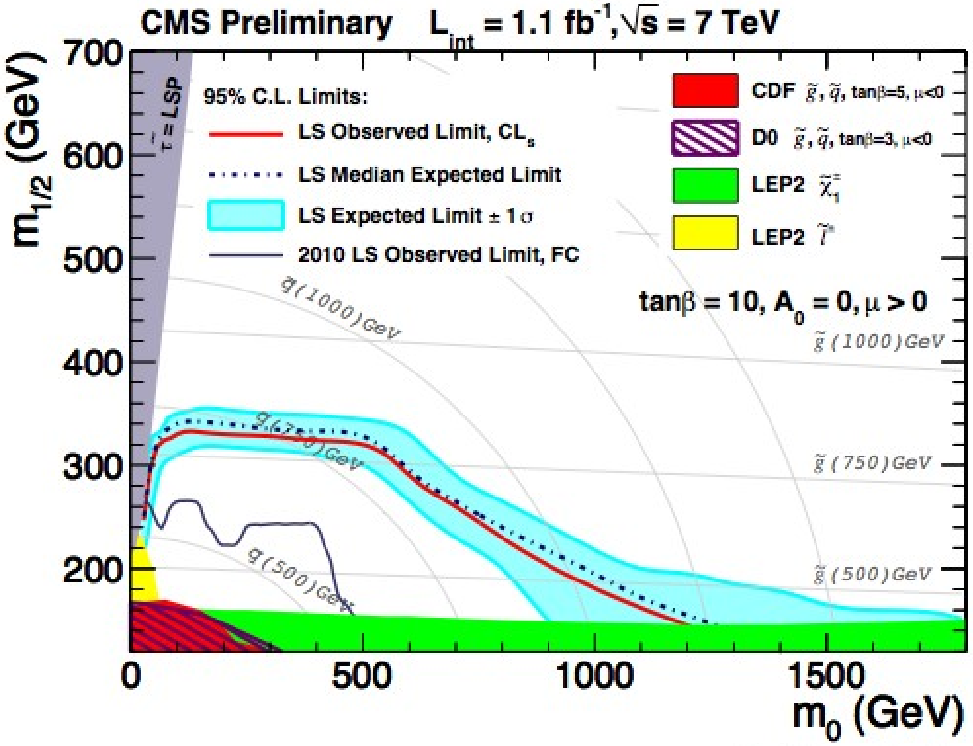
MET predictions in data, e+μ channel



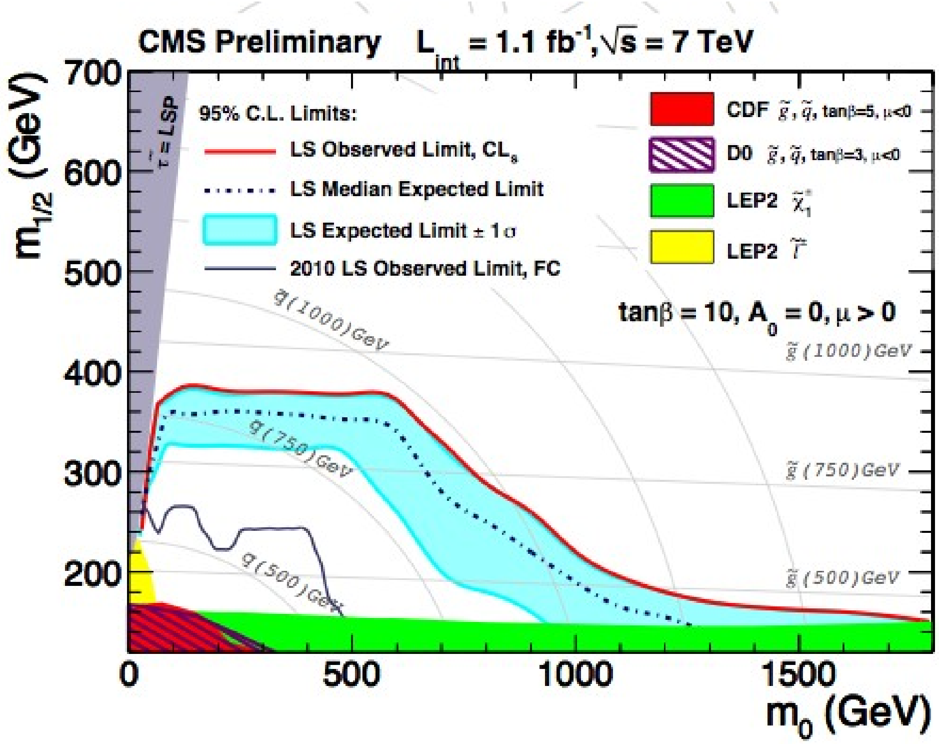


Lepton Spectrum exclusion plots

Loose selection (H_T>500, MET>250)



Tight selection (H_T>500, MET>350)



Signal efficiency uncertainties:

Taken into account (% effect on efficiency):

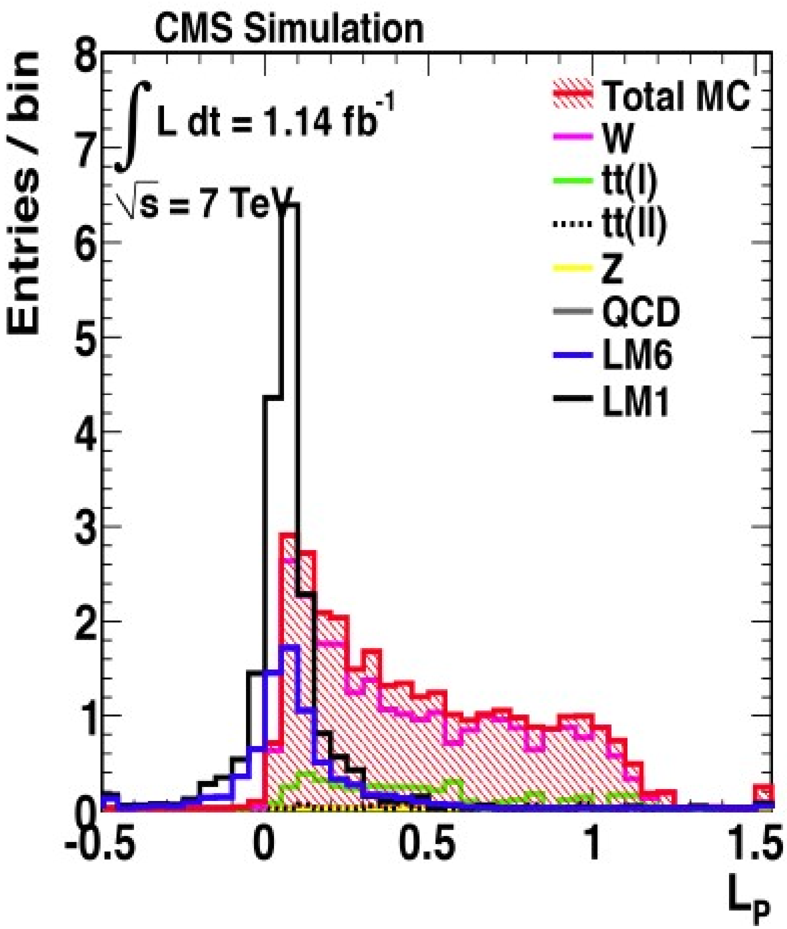
- **JES ~ 10%**
- **NLO effect ~ 10-18%**
- **Lepton efficiency (5%)**
- **Luminosity uncertainty (4.5%)**

Apply 20% uncertainty flat in m_0,$m_{1/2}$ plane.

Systematic uncertainties on background prediction also taken into account. See backup slides for table of systematics.

Lepton-Projection (L_P) Method

Lepton Projection (L_P) variable



$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

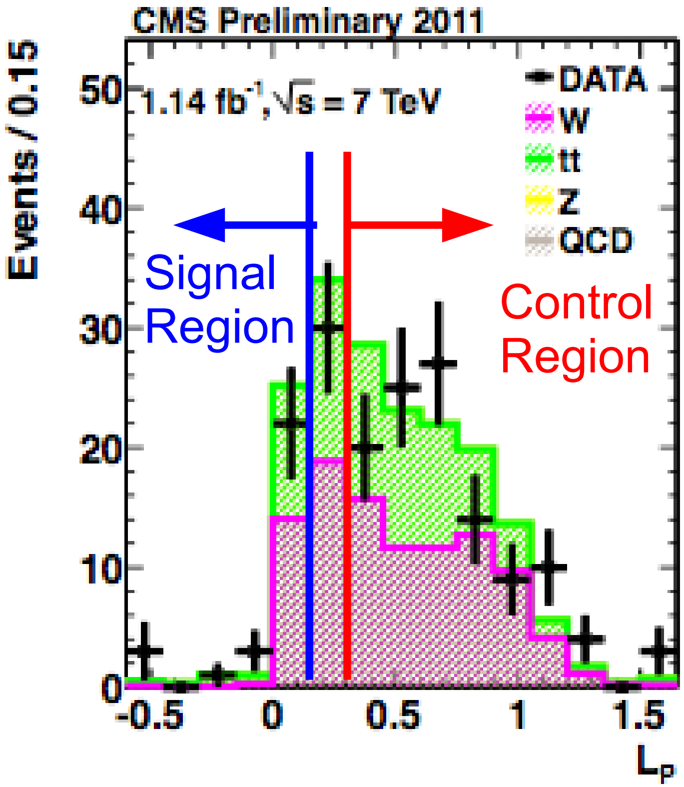
- L_P is a polarization variable, very highly correlated to $\cos(\theta^*)$; $L_P \rightarrow 1/2(1+\cos(\theta^*))$ at high $p_T(W)$
- Fit of L_p templates were used to measure W polarization in W+jets events at CMS PRL 107 (2011) 021802
- L_P uses both angle (MET, lepton) and momenta to separate SUSY/SM

Perform search in L_P , binned in S^{lep}_T
S^{lep}_T good measure of energy in leptonic sector, without effecting lepton-neutrino correlation

$$S^{lep}_T = |p_T(\ell)| + |\not{E}_T|$$

L_P background method

Muon Channel, $250>S_T>350$ GeV



- $\geq$3 jets, H_T>500 GeV
- Search in L_P variable in 3 bins of S^{lep}_T: S^{lep}_T = 250-350 GeV, 350-450 GeV, 450+ GeV
- Also check method in bin of lower S^{lep}_T, 150-250 GeV
- Estimate number of SM background in signal region by multiplying control region by R_{CS}, translation factor from MC

$$R_{CS} = \frac{\text{Number of events with } L_P < 0.15}{\text{Number of events with } L_P > 0.3}$$

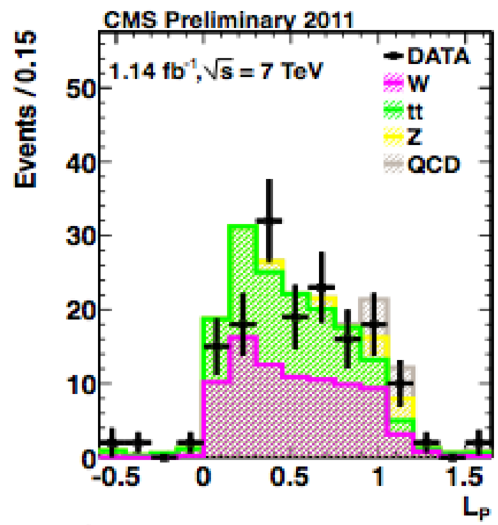
R_{CS}: translation factor to extrapolate from control to signal region:

$$N_{SMpred}(L_P < 0.15) = R_{CS} N_{data}(L_P > 0.30)$$

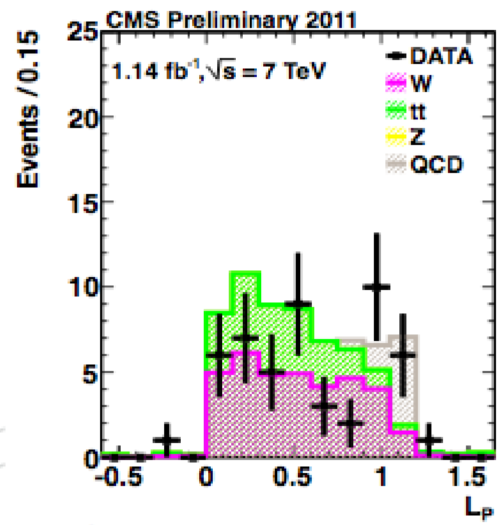
L_P distribution in different bins of S^{lep}_T

Electrons

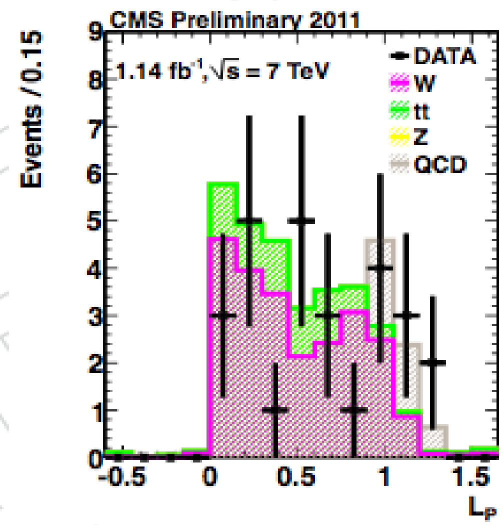
$250<S^{lep}_T<350$ GeV



$350<S^{lep}_T<450$ GeV

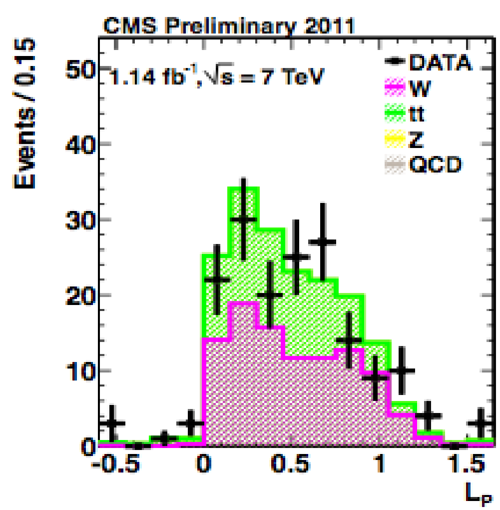


$S^{lep}_T>450$ GeV

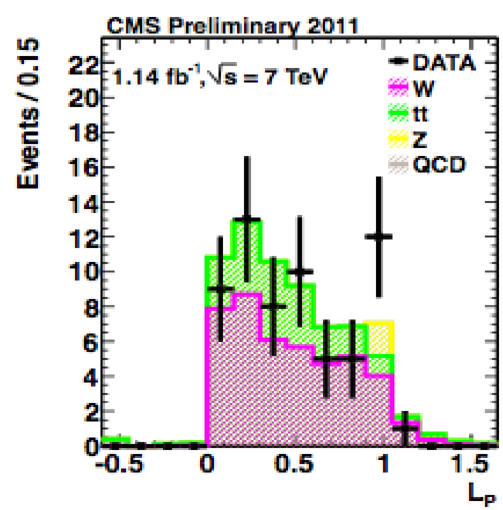


Muons

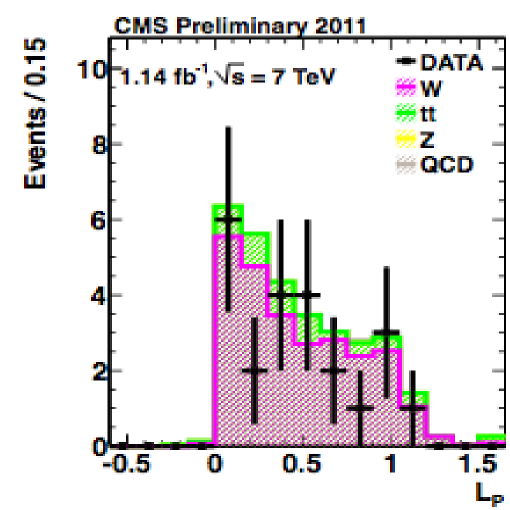
$250<S^{lep}_T<350$ GeV



$350<S^{lep}_T<450$ GeV



$S^{lep}_T>450$ GeV



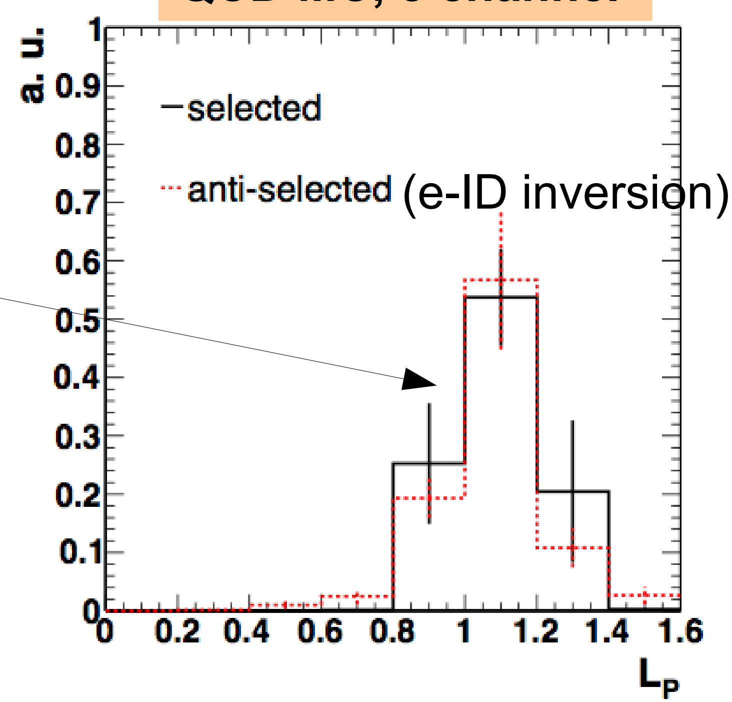
Good agreement between data and MC; electron channel has more QCD

QCD prediction in the L_P method

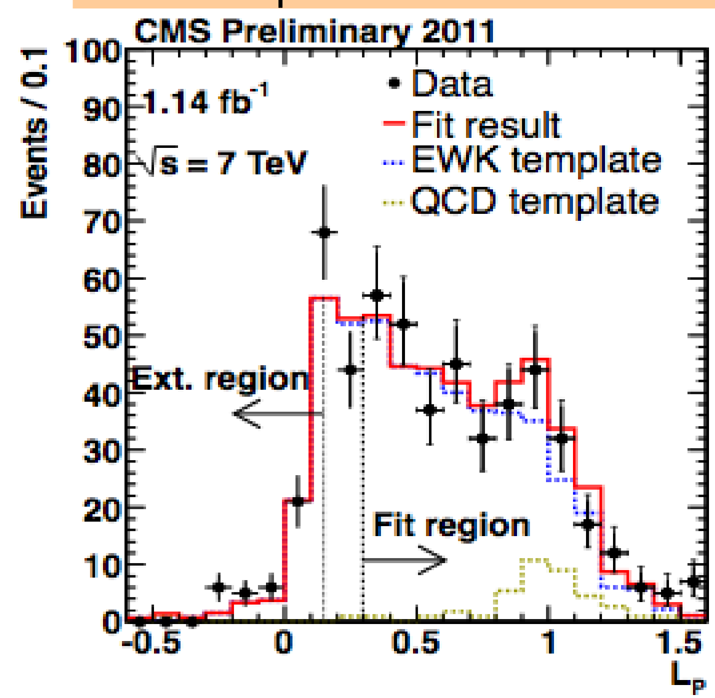
- In μ channel, perform data-driven method using isolation of the muon and MET to show QCD negligible (similar to lepton spectrum method)
- In e channel, larger QCD contribution, especially in control region
  - Fit L_P variable in signal region (L_P>0.3) with EWK (ttbar & W+jets) L_P template from MC and QCD L_P template from data (electron-ID inversion). Then extrapolate fit to signal region (L_P<0.15) to obtain final QCD and EWK number

Shows it is possible to get a QCD data template by inverting electron ID

QCD MC, e channel



150<S^{lep}_T<250 GeV, e channel



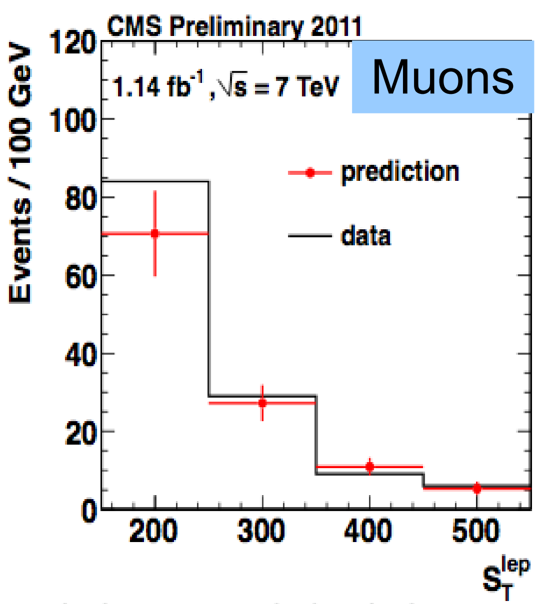
Results, L_P method

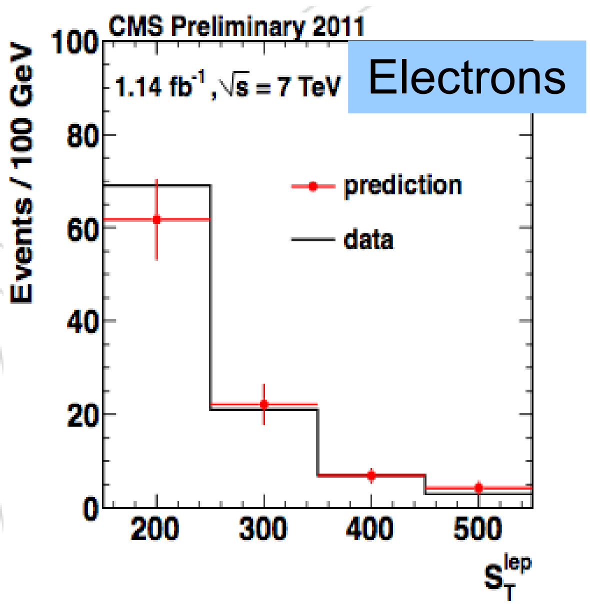
Muons

	Control Region (L_P >0.3)		Signal Region (L_P <0.15)		
S_T^{lep} Range (GeV)	Total MC	Data	Total MC	SM estimate	Data
[150-250]	385±7	368	73.9±3.0	70.6±11	84
[250-350]	116±2	112	28.1±1.1	27.2±4.6	29
[350-450]	43.4±2.	41	11.5±0.7	10.9± 2.3	9
> 450	18.4±0.8	15	6.5±0.4	5.3± 1.8	6

Electrons

	Control Region (L_P >0.3)			Signal Region (L_P <0.15)			
S_T^{lep} Range (GeV)	QCD	EWK	Data	QCD	EWK	SM estimate	Data
[150-250]	39.5±15.5	350±24	390	1.0±0.3	60.8±4.1	61.8±8.7	69
[250-350]	5.0±5.2	117±12	122	0	22.2±2.2	22.2±4.4	21
[350-450]	7.1±3.9	28.9±6.2	36	0	6.9±1.5	6.9±1.7	7
> 450	6.5±5.7	12.5±3.8	19	0	4.3±1.3	4.3±1.5	3

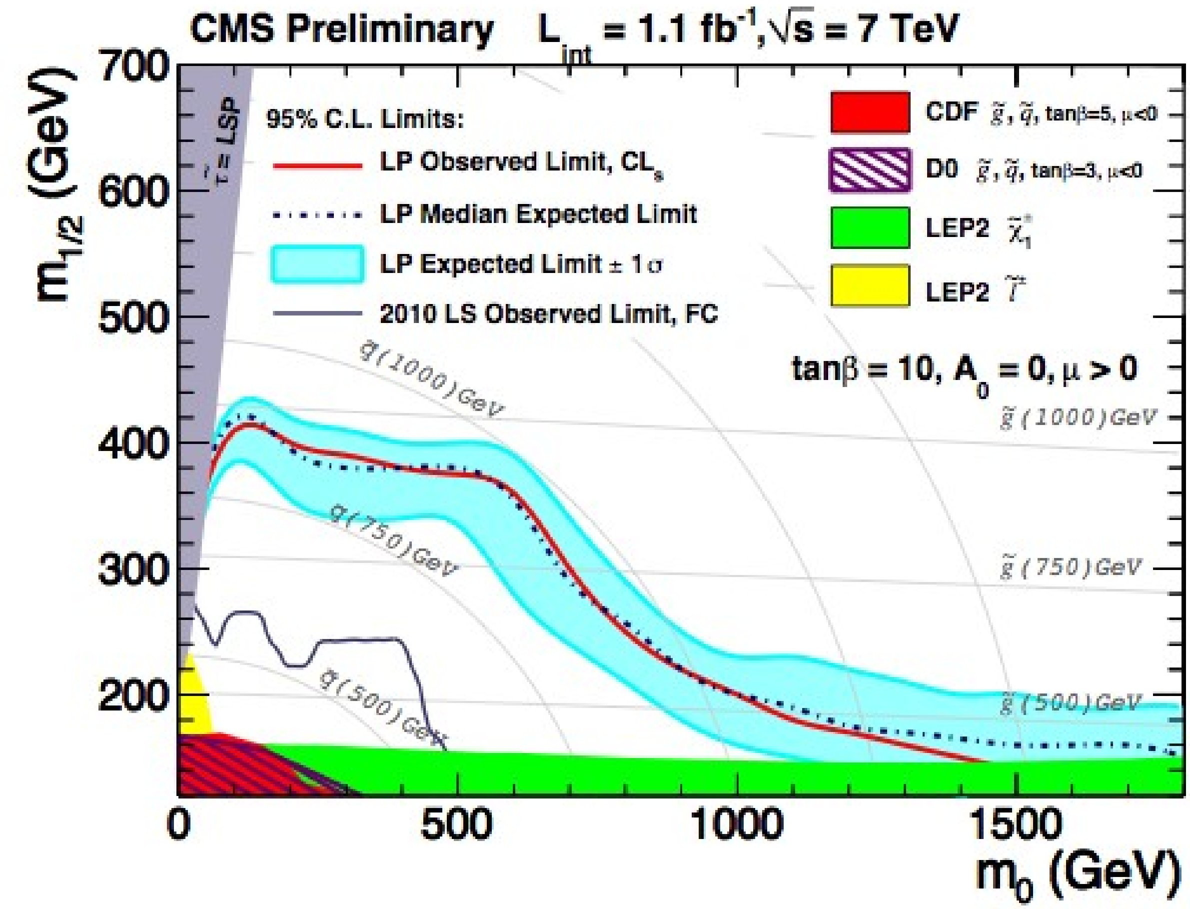




- **SM estimates agree with observation within uncertainties**
- **No signs of excess observed**

Dominant systematic uncertainty is number of events in control region (see backup slides)

L_P exclusion plot

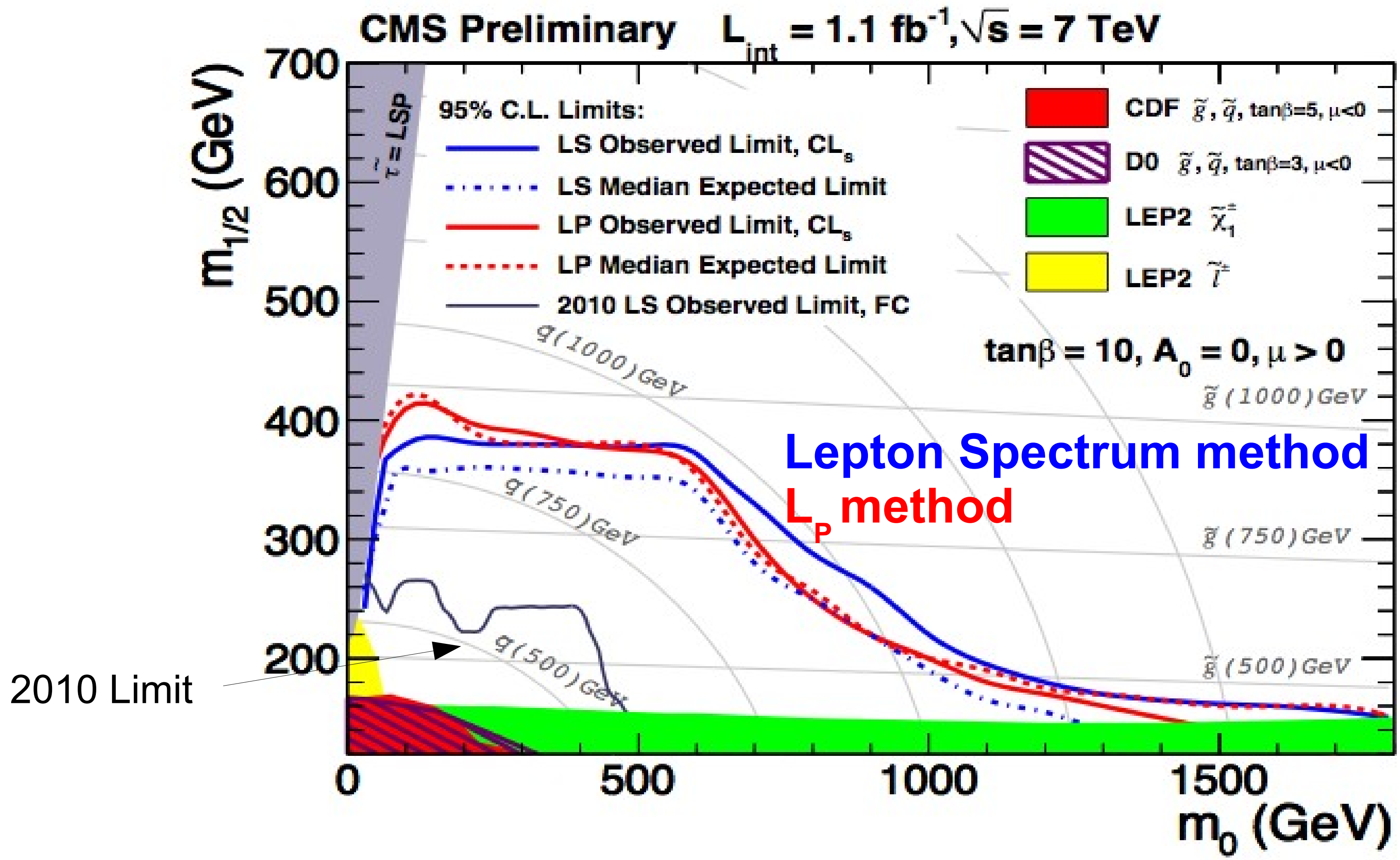


Signal efficiency uncertainties:

uncertainty	values
$\mathcal{L}$	4.5%
trigger efficiency	1%
JES 5%	10%-15%, varies between SUSY grid points
$\not{E}_T$ resolution 10%	1%-15%, varies between SUSY grid points
PDF and NLO	10%

Exclusion limit takes into account predictions in each of the bins of S^{lep}_T (except S^{lep}_T 150-250 GeV bin) and uncertainties on signal efficiency and background prediction (see backup slides for tables of background prediction systematics)

Lepton Spectrum and L_P exclusion plots



Limits for both methods very similar; constrain gluino mass to be >~900 GeV (for m_0<500 GeV, tanβ=10)

Conclusions

1. Single lepton sample (e and μ) with very loose selection requirements, consistent with SM simulation. Conclude:
   (a) Sample dominated by SM backgrounds, i.e., W+jets and ttbar
   (b) No evidence for large non-SM contribution
   (c) We can use the sample to estimate SM with data-driven methods
2. Apply two different data-driven background prediction methods, both which rely on known properties of W polarization in ttbar and W+jets.
   (a) Lepton Spectrum: data p_T(lepton)$\rightarrow$MET
   (b) Lepton Projection: data L_P(high)$\rightarrow L_P$(low)
3. Good agreement between predicted and observed yields for both methods. Also good agreement of shapes.
   (a) Lepton Spectrum method: shape of MET distribution
   (b) Lepton Projection: shape of L_P distribution (control/signal samples)
4. CMSSM Exclusion plots from both methods.
   (a) Constrain gluino mass to be >~900 GeV (for m_0<500 GeV, $\tan\beta$=10)

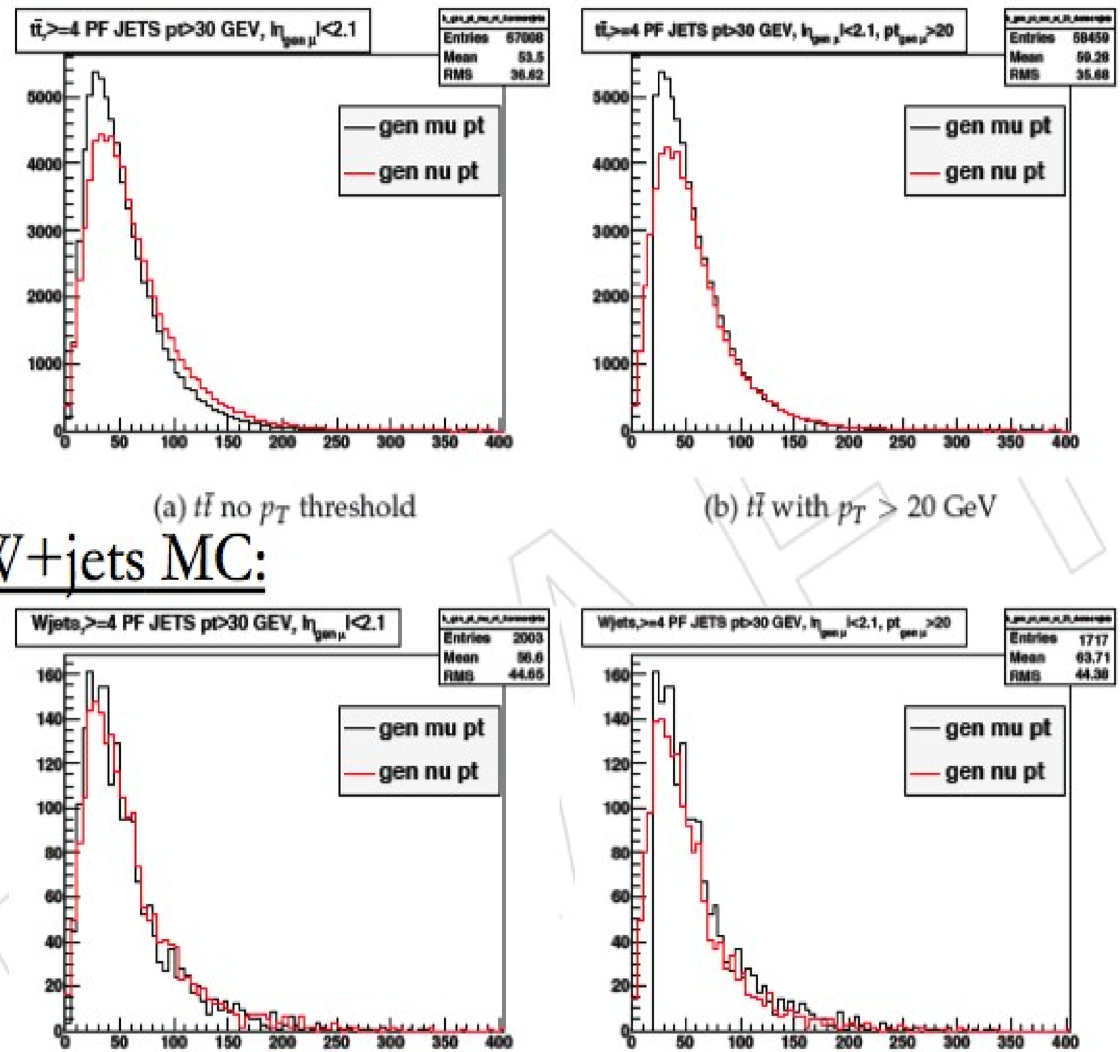
Backup Slides

Generator level mu, nu p_T

ttbar MC:

- The genuine MET is modeled based on the muon P_T spectrum;
- Corrections for residual differences between the two spectra are obtained from MC.

W+jets MC:



(a) $t\bar{t}$ no p_T threshold

(b) $t\bar{t}$ with $p_T > 20$ GeV

(c) W + jets, no p_T threshold

(d) W + jets, with $p_T > 20$ GeV threshold

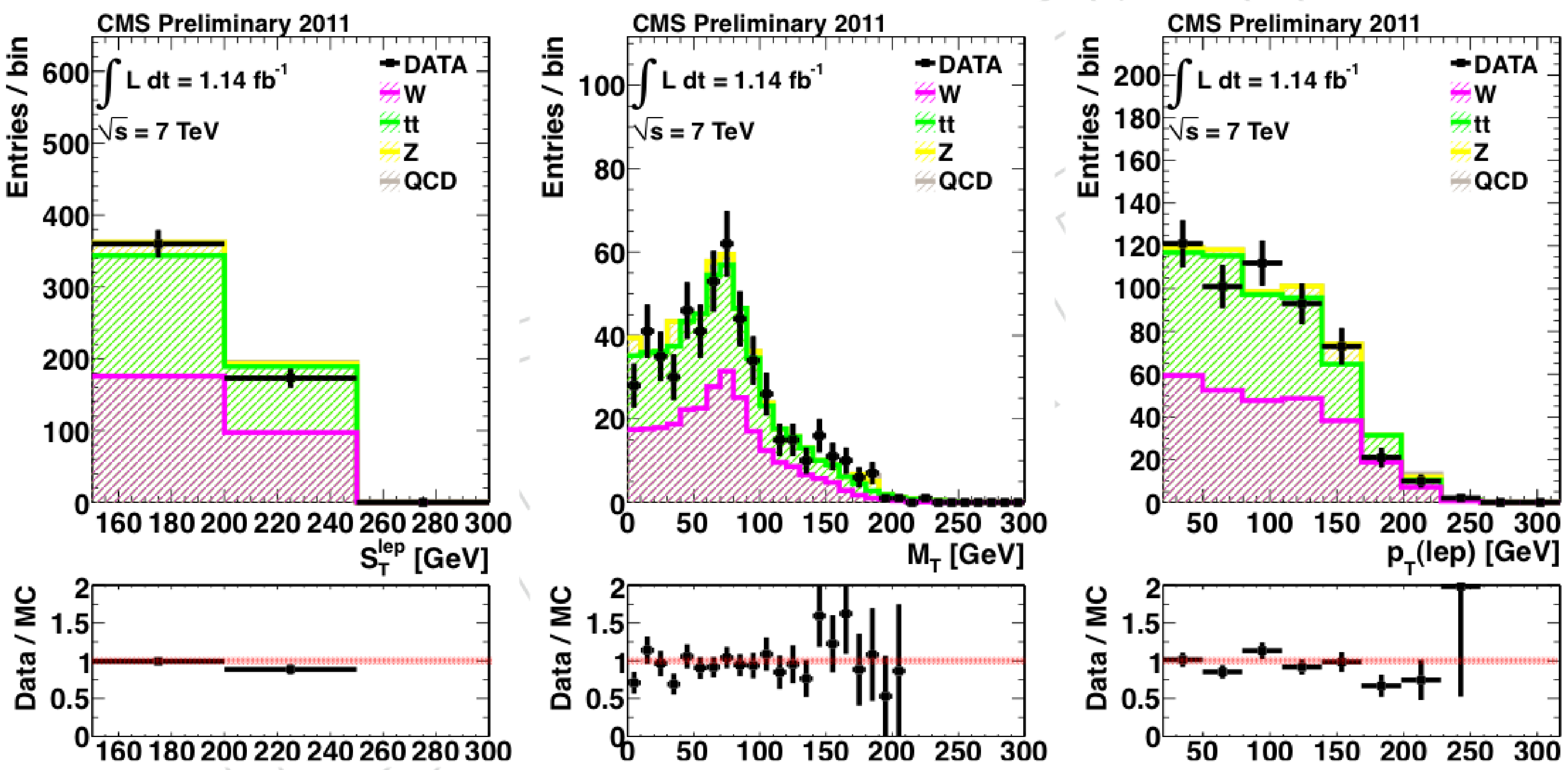
NB: the electron P_T spectrum has significant QCD contamination and is not used today (but should be included later in 2011).

Systematics Lepton Spectrum Method

Source	$\Delta(N_{\text{predicted}}/N_{\text{true}})(\%)$ (Loose selection)	$\Delta(N_{\text{predicted}}/N_{\text{true}})(\%)$ (Tight selection)
$\not{E}_{\mathrm{T}}$ and jet energy scale	23	31
W polarization in $t\bar{t}$	4	1.4
W polarization in W+jets	9	15
$\sigma(t\bar{t})$ and $\sigma(W)$	16	16
Lepton efficiency (μ) vs. p_T	4	4
Lepton efficiency (e) vs. p_T	4	4
Backgrounds in control sample	7	7
Total	31	39

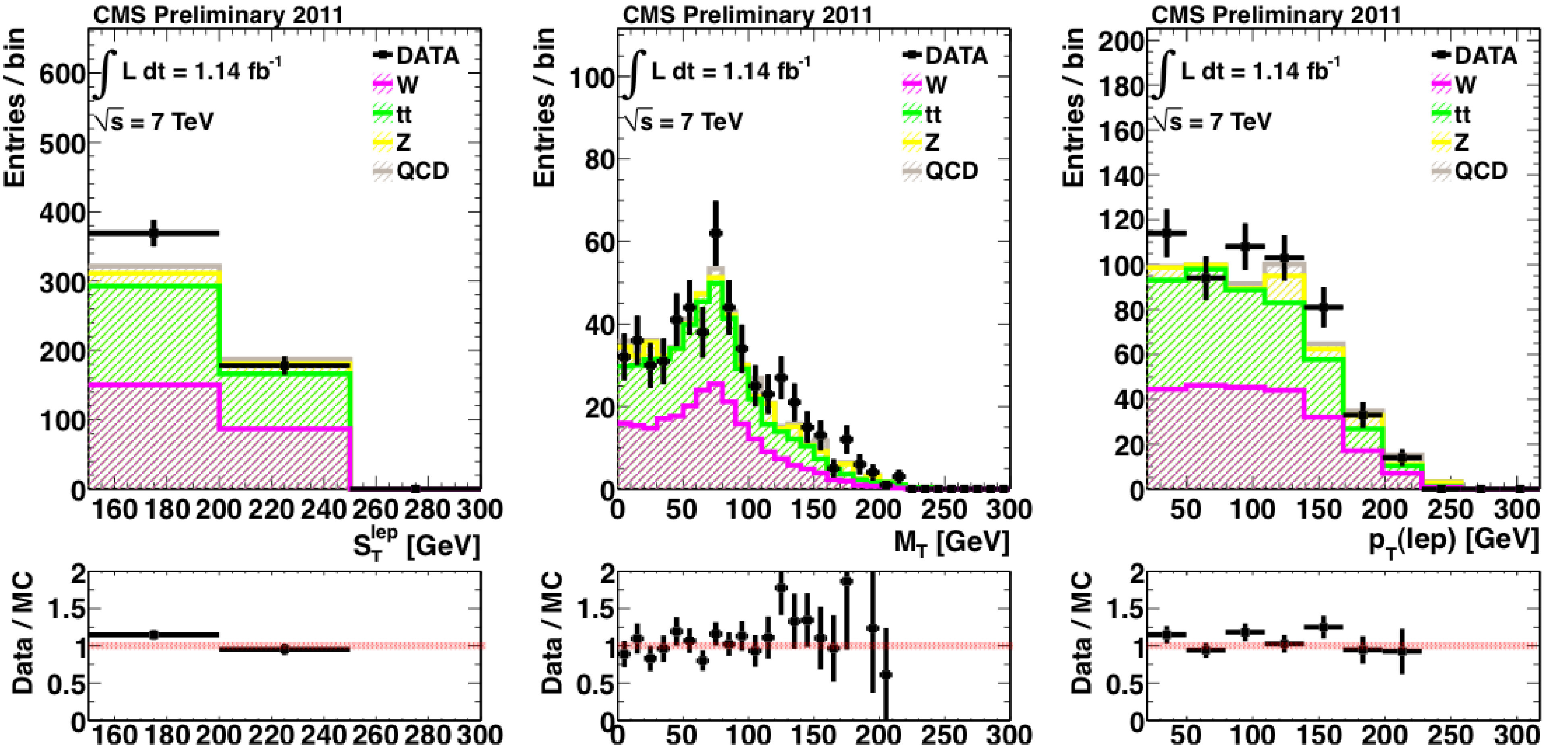
L_P method, kinematic dist. (muon channel)

Data and MC comparison for muon events from the preselection and with S^{lep}_T = 150-250 GeV



L_P method, kinematic dist. (electron channel)

Data and MC comparison for electron events from the preselection and with S^{lep}_T = 150-250 GeV



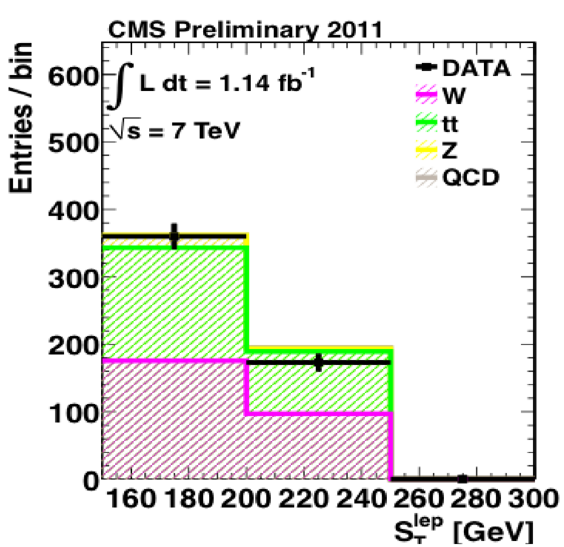
Mu Channel: L_P yields in different bins of S^{lep}_T

MC numbers

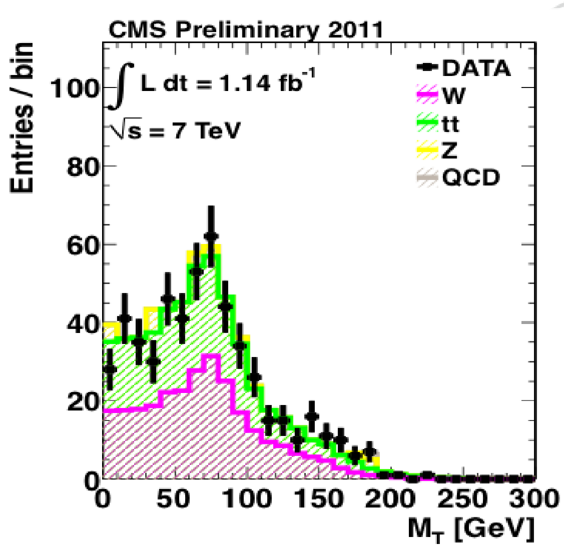
$L_P < 0.15$	Muons: S_T^{lep} range (GeV)		
Sample	[250-350]	[350-450]	[450-inf]
$t\bar{t}$ (ℓ)	11.4±0.9	2.91±0.4	0.8±0.2
$t\bar{t}$ ($\ell\ell$)	2.2±0.4	0.6±0.2	0.1±0.1
W	14.5±0.6	8.0±0.5	5.6±0.4
Z	0±1.5	0±1.5	0±1.5
Total MC	28.1±1.1	11.5±0.7	6.5±0.4
LM1	24.2±0.9	23.1±0.9	16.2±0.7
LM3	24.8±0.8	16.7±0.6	9.7±0.5
LM6	1.9±0.0	2.5±0.1	5.9±0.1

- In MC, W+jets dominant background, especially at high S^{lep}_T

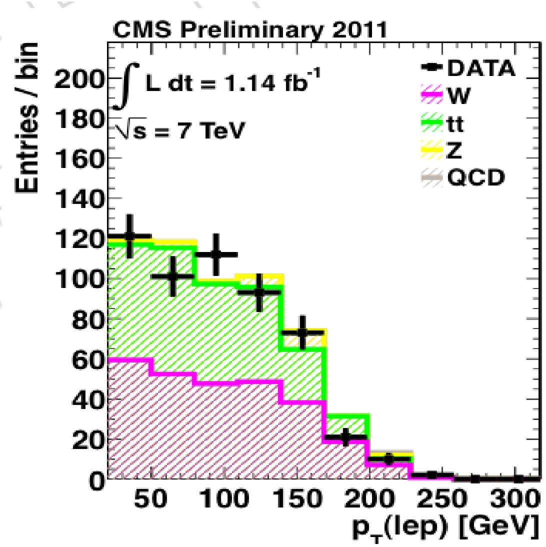
$250<S^{lep}_T<350$ GeV



$350<S^{lep}_T<450$ GeV



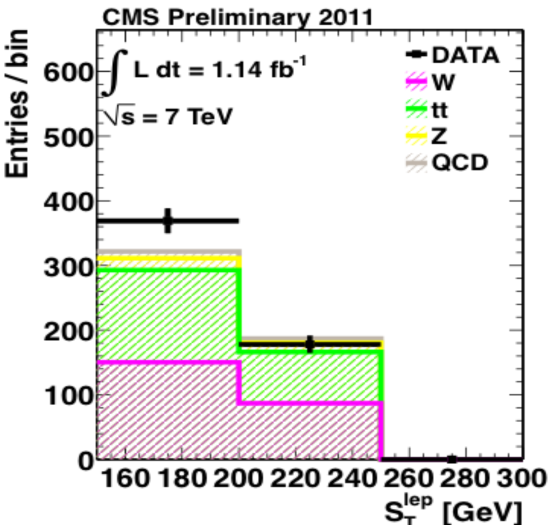
$S^{lep}_T>450$ GeV



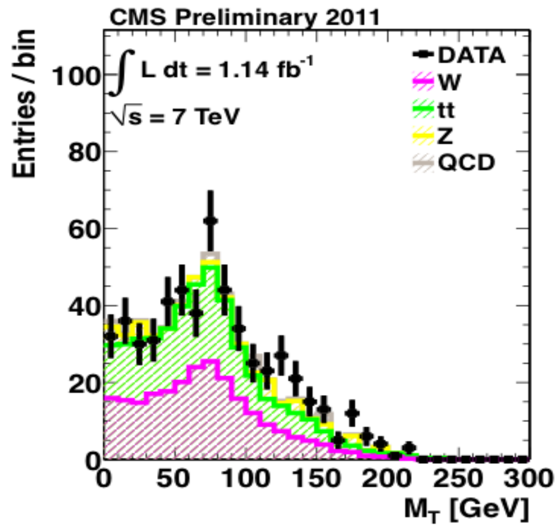
e Channel: L_P yields in different bins of S_T

$L_P < 0.15$	Electrons: S_T^{lep} range (GeV)		
Sample	[250-350]	[350-450]	[450-inf]
$t\bar{t}$ (ℓ)	7.8±0.7	3.0±0.4	1.0±0.3
$t\bar{t}$ ($\ell\ell$)	2.4±0.4	0.7±0.2	0.4±0.2
W	10.5±0.5	5.2±0.4	4.7±0.3
Z	0±1.5	0±1.5	0±1.5
Total MC	20.8±1.0	8.8±0.6	6.1±0.5
LM1	22.9±0.9	20.8±0.8	14.7±0.7
LM3	22.8±0.7	14.8±0.6	9.7±0.5
LM6	1.7±0.0	2.3±0.1	5.3±0.1

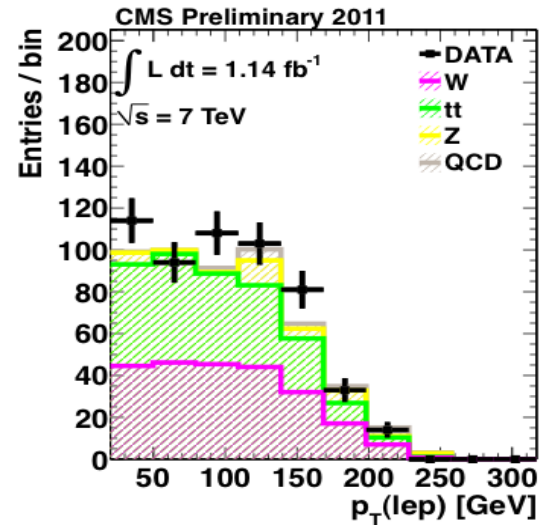
$250 < S_T < 350$ GeV



$350 < S_T < 450$ GeV



$S_T > 450$ GeV



Systematics L_P Method (muons)

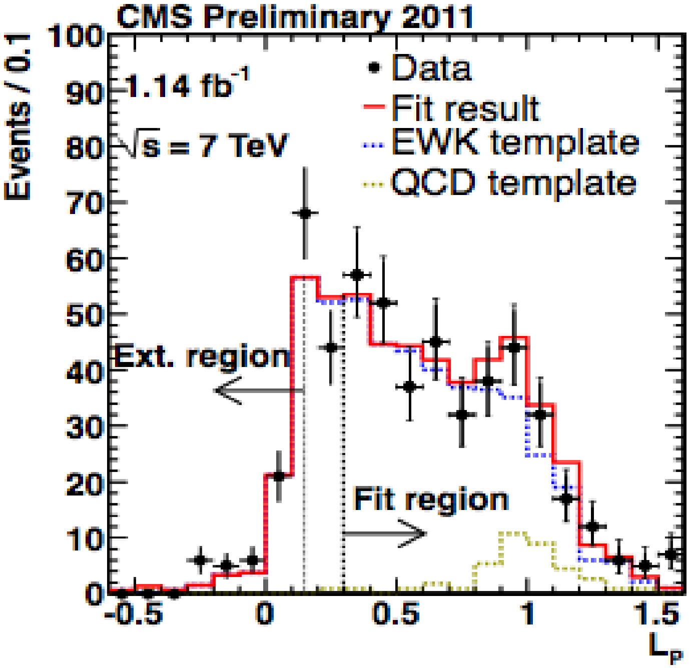
$S_T^{lep} \in$	[150-250]	[250-350]	[350-450]	> 450
R_{CS}	0.19	0.24	0.26	0.35
$\Delta N/N$ at 1.1 fb^{-1} (%)	13	21	36	41
Systematic Uncertainty (%)	15	17	21	34
Control Region Statistics (%)	5	10	15	24
MC Statistics (%)	4	4	8	8
JES Uncertainty (Flat 5%) (%)	10	9	8	19
MET Resolution (10%) (%)	1	3	2	3
Lepton pT Scale (%)	2	2	1	3
$W/t\bar{t}$ Ratio (%)	5	5	6	10
$t\bar{t}$ ($\ell\ell$) (%)	5	4	2	1
W Polarization (%)	1	1	2	2
$t\bar{t}$ Polarization (%)	5	5	5	5

Systematics L_P Method (electrons)

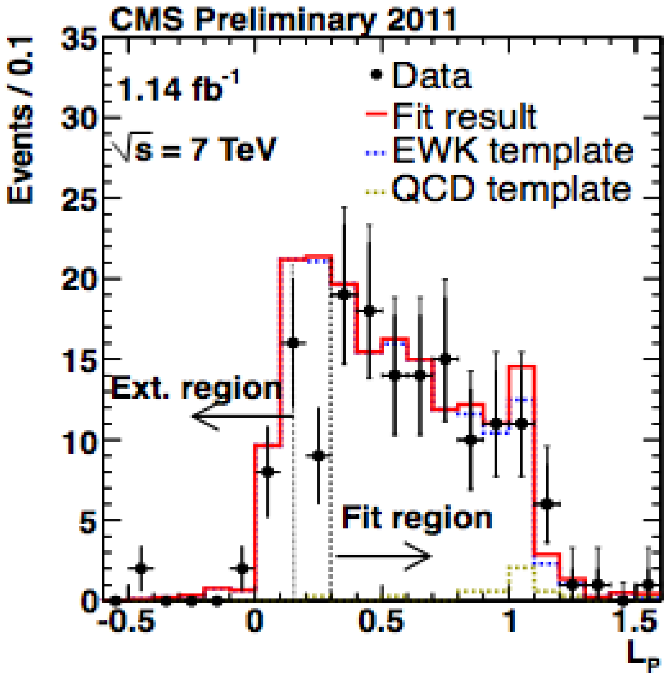
$S_T^{lep} \in$	[150-250]	[250-350]	[350-450]	>450
R_{CS}	0.16	0.18	0.19	0.23
$\Delta N/N$ at 1.1 fb^{-1} (%)	12	22	38	58
Systematic Uncertainty (%)	14	20	24	34
Control Region Statistics (%)	5	9	17	24
MC Statistics (%)	1	10	7	8
JES Uncertainty (Flat 5%)(%)	9	10	10	19
MET Resolution (10%) (%)	2	2	5	7
$W/t\bar{t}$ Ratio (%)	6	7	6	10
$t\bar{t}$ $(\ell\ell)$ (%)	6	7	6	2
W Polarization (%)	1	1	2	3
$t\bar{t}$ Polarization (%)	5	5	5	5

L_P: additional electron QCD fit plots

$150 < S^{lep}_T < 250$ GeV



$250 < S^{lep}_T < 350$ GeV



Lepton Projection (L_P) variable

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

Fit of L_p templates were used to measure W polarization in W+jets events at CMS
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